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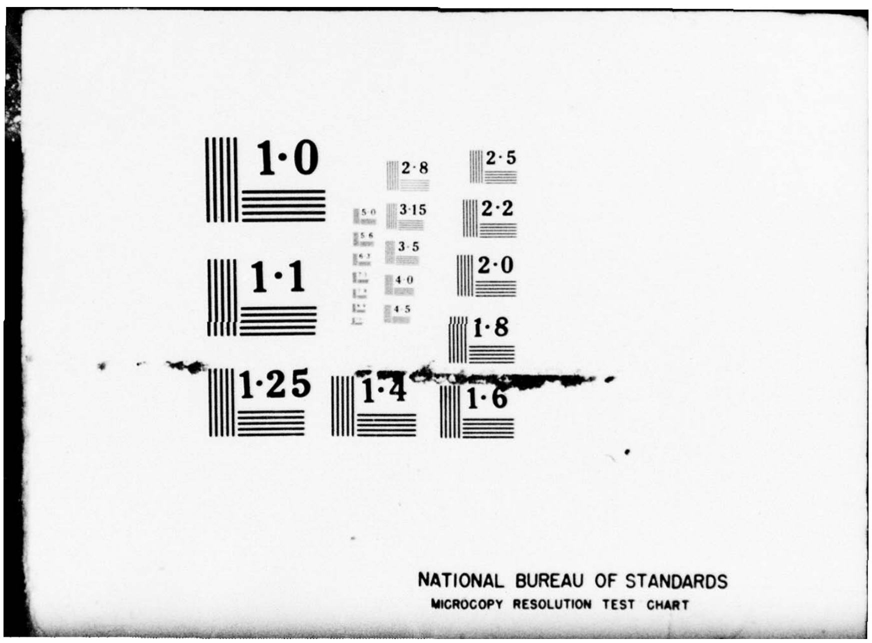
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ENERGETICS: SYSTEMS ANALYSIS WITH APPLICATION TO WATER RESOURCES PLANNING AND DECISION MAKING

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DECEMBER 1977 IWR CONTRACT REPORT 77-6

ENERGETICS:

SYSTEMS ANALYSIS WITH APPLICATION TO WATER RESOURCES PLANNING AND DECISION-MAKING

A Report Submitted to:

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Report evaluates energetics as a possible analytical tool for use in water resource planning and decision-making. Basic scientific concepts which comprise the comprehensive subject of energetics are explained through the use of easily understood correlaries. The author examines the potentials which these concepts have in water resources work as well as the limitations which curtail their present useability and acceptance. He concludes that energetics has promise as an analytical tool and recommends further development and testing in actual water resource planning situations.

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It gives me a great deal of pleasure to acknowledge the enormous contribution of Dr. H. T. Odum to the measurement of environmental impact through the concept of energetics. My thanks go to the Corps of Engineers, Institute for Water Resources and to Richard Reppert for his advice and counsel toward writing this paper.

PREFACE

The U.S. Army Corps of Engineers has had an interest in energetics--defined here as the evaluation of natural and manmade systems using energy as the basis for analysis--since mid-1974. It was at that time that Professor Howard T. Odum of the University of Florida at Gainesville, originator of modern day energetics theory, suggested to then Chief of Engineers, LTG William C. Gribble, that energetics analysis had the potential for application in water resource planning and decision-making.

In late 1974 the U.S. Army Engineers Institute for Water Resources (IWR) at Fort Belvoir, Virginia, was directed to undertake the necessary studies and to evaluate that potential. To conduct this evaluation, IWR reviewed all the significant literature available on the subject of energetics, and sponsored two separate research studies at the University of Florida. These studies were geared to directly compare energetics with benefit/cost analysis traditionally used in water resource plans and programs.

One research study involved the development of such comparisons for alternative water resource strategies associated with the authorized multiple purpose project for the Upper St. Johns River in Florida. The other study involved the evaluation of alternative modes for bulk commodity transportation and was specifically geared to net energy analysis of railroad, barge, and slurry pipeline systems, with coal as the bulk commodity in question.[1]

Following completion of these research studies, IWR retained Caldwell D. Meyers, Environmental Consultant, to pull together the results of this research and the mass of other literature into a single, summary report. This is Mr. Meyers' report. In addition to defining energetics and explaining the underlying concepts and procedures which make up this complex subject, the report discusses the application of energetics to water resources planning and decision-making.

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[1]Contractor's report entitled "A Comparison of Energetics and Economic Benefit Cost Analysis for the Upper St. Johns River," Bayley, et al, June 1976, is in draft form with no present plans to make it available for general distribution. Contractor's report entitled "Energetics and Systems Modeling: A Framework Study for Evaluation of Alternative Transportation Modes," Bayley, et al, June 1977, is in press with distribution anticipated in early 1978.

Mr. Meyers concludes that in spite of definite limitations which tend to curtail its present usability and acceptance as an analytical tool, energetics does have considerable potential which should be further developed and tested. Accordingly, Mr. Meyers recommends that the Corps continue its interest in this subject and provide for the test application of energetics in a series of active planning situations.

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INTRODUCTION

PURPOSE AND OBJECTIVES

The purpose of this paper is to report on the energetics approach of H. T. Odum[1] as a possible tool for the analysis of environmental impact, expecially as it may be applied to water resources planning and decision making by the U. S. Army Corps of Engineers. The objectives of this effort are:

(1) To select concepts from Odum's comprehensive philosophy which have immediate relevance to problems in water resources;

(2) To present a simplified coherent version of these concepts, illustrating their application through a discussion of published research wherever possible, such that energetics becomes a useful tool to both trained resource planners and to those with a limited environmental background;

(3) To compare the application of this analytic approach with other methods of environmental accounting including traditional economic techniques of benefit/cost analysis;

(4) To present conclusions and recommendations which enable the Corps of Engineers to determine the usefulness of the energetics approach to their current mission.

BACKGROUND

The U. S. Army Corps of Engineers (C. of E.) is a military branch established in 1775 to engineer fortifications and move fighting men. After the Revolution, the Corps became a peacetime civil works arm of the federal government and its growth traces expansion of this nation. Corps engineers were active in exploration and mapping the land and water as the population began to move across the continent, as well as erecting bridges, jetties, breakwaters and harbor structures to facilitate transportation. Corps involvement

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increased as western settlements developed and the need for canals and river improvements for transportation of supplies and products became evident. The River and Harbor bill of 1824 authorized improvements in the Mississippi and Ohio (charting, sandbar marking and snag removal) and gave the Corps explicit responsibility toward development of rail transportation. These efforts by the Corps had a great impact on the rate and level of expansion during the formative years of the country.

Subsequent to geographic expansion, the Corps became heavily involved in protection of the lands through flood control projects, and in large-scale water resources projects to supply water to the burgeoning population. Development of resources increased and construction of dams, hydroelectric facilities and harbor structures moved forward at a rapid pace. This was a phase of economic and industrial expansion in which structures were emphasized.

During the latter phases of this expansion around 1920, the Corps was enjoined by Congress to develop comprehensive river basin plans and scientific resource-related research to aid in program evaluation and in planning for future water needs. Regulations within the Corps required preparation of milestone plans for justification and evaluation of individual projects that seemed excessive to citizens impatient to protect their land, their towns and their economic investments. On one hand, there was encouragement to build and on the other, constraint, forcing the Corps to continuing project evaluation. The Flood Control Act of 1936 was an initial step in large scale water resources development.

In 1965, Congress recognized the necessity for a comprehensive national assessment and program for the wise use and protection of the water resources by passing the Water Resources Planning Act (Public Law 89-90). This Act created the Water Resources Council with a membership at cabinet level from federal resource-oriented agencies. The Corps has had a strong interest and role in the Council's deliberations and has brought to it strengths in development and planning large-scale water resource projects.

In 1969, Congress gave evidence of the growing national environmental awareness through the National Environmental Policy Act (Public Law 91-190). This imperative expressed Congress' desire "to develop a national policy which will encourage productive and enjoyable harmony between man and his environment. . ." It enunciated an ethic for guidance of all federal agencies; required preparation of Environmental Impact Statements (EIS) where federal actions were

expected to have significant environmental effects, and established the Council on Environmental Quality in the Executive Branch, with responsibilities for oversight and guidance of EIS preparation, preparation of an annual report on national environmental conditions, and a general advisory capacity to the President. This Act had great impact on Corps activities forcing further extensive evaluation of proposed and current projects, and publication of a new form: The Environmental Impact Statement.

Legislative pressure to clean up the nation's seriously degraded waters was increased through the Federal Water Pollution Control Act amendments of 1972 (Public Law 92-500). This directly affected the Corps through its delegation of permitting authority for discharge of dredged and fill materials to the Chief of Engineers. Since over 90 percent of national dredged spoil is generated by the Corps, project evaluation processes were again strengthened, and subsequently, a Supreme Court decision in 1975[1] forced expansion of this permit program to marsh and wetland areas not included previously.

Studies by the Water Resources Council acting under the authority of the Water Resources Development Act of 1974 (Public Law 93-251) also affected Corps planning and project financing.

This recitation only highlights legislative pressures toward national environmental improvement; numerous other legislation and regulations (pp. 1-18 to 1-25; U. S. Army Corps of Engineers, 1976) underscore the key role of the Corps toward restoring and maintaining a high level of water quality and planning for the future of water resources in the U. S.

In many respects, and despite criticism from in and out of government, the Corps does not regard recent environmental concerns as new challenges, having been active in planning and evaluation since the 1800's. However, the national mood has become increasingly one of question, and demand for public involvement.

To the Corps, public opinion has been an integral part of project planning beginning with the initial request for resource-related problem solving through Congressional representatives. At at least four points prior to construction,

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[1] _National Resources Defense Council v. Callaway_, 392 F.Supp. 685 (D.D.C., 1975).

public input is solicited for planning or evaluation on a formal or informal basis (pp. x to xi; U. S. Army Corps of Engineers, 1975). By regulation,[1] formulation of alternatives, impact assessment and project evaluation are rigorous and scheduled to occur at least three times prior to development of detailed construction plans. The question that immediately arises in this regard is "How adequate are the analytic tools for such assessment and evaluation?"

In the "Manual for Water Resources Planners" (U.S. Army Corps of Engineers, 1976), the evolution of thought regarding the role of environmental studies in Corps planning is briefly discussed. That role is best expressed by the following statement: "EQ [Environmental Quality] will share equal attention with the NED [National Economic Development] objective during plan formulation." Indicating the planners' response to this, the purpose of environmental studies is stated to include: determining pertinent ecological relationships; providing information to interested publics; preparation of an Environmental Impact Statement; monitoring pre-, during and post-construction relationships and changes; assessing impacts of proposed actions; and accumulating baseline data for future planning. Types of environmental investigations mentioned are: (1) inventories, (2) special studies, and (3) monitoring.

Recognition of the dual importance of environmental and economic studies adds a great weight to Corps responsibilities. However, in Chapter 7 of the same planning manual mentioned above (U. S. Army Corps of Engineers, 1976), the difficulties in dealing with impacts are summarized by the statements: "The significance of an impact is often subjective in nature. . .", and "Whether or not an impact is by nature beneficial or adverse is often subject to personal interpretation." This, in fact, summarizes the frustration faced by whole hosts of decision makers in their attempts to deal quantitatively with the inexactnesses and complexities of environmental systems. It seems clear that when one wishes to measure or understand human impact on a natural system, the approach involves measurement of at least three separate aspects: the physics, the chemistry and the biology of the system.

Measurement of physical change and prediction of future changes may be accomplished with a high degree of accuracy using relatively sophisticated and reliable tools; chemical

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[1] Department of the Army, Office of the Chief of Engineers. Engin. Reg. 1105-2-200, 10 November 1975. Planning Process: Multiobjective planning framework.

tools are similarly well developed; but in dealing with the biology, one is confronted with a young science, and a system which is undergoing profound change even without human interference -- the target is moving. Therefore, when one summarizes all these factors into "the ecology" or the environmental quality, human frailty and the inability to digest this great complexity become too soon evident.

Numerous attempts have been made to reduce the complexity of environmental quality to a manageable body of information on which to make rational, responsible decisions, some by the Corps. This paper itself is an expression of the Corps' intention to grapple with a current problem of profound national concern.

PREVIOUS STUDIES

One approach to the problem of decision making in environmental quality has been proposed by Leopold, et al. (1971), to aid the U. S. Geological Survey in program planning. A comprehensive matrix and a weighting system make up the essense of the method and its chief value to this field has been to underscore the large number of parameters and vast amount of data necessary in making responsible decisions.

A paper by Whitman, et al. (1971) reports on a team approach to environmental evaluation. The Delphi method (Pill, 1971), where a group of people isolate themselves to develop answers through their collective intuition and experience, forms the backbone of this method. This methodology plus further study at the same institution (Battelle Columbus) resulted in papers by Dee, et al. (1972) and Dee, et al. (1973). The latter paper was developed by an interdisciplinary research team and is based on an hierarchy of indicators of environmental quality. The four major categories of indicators were ecology, environmental pollution, esthetics and human interest subdivided into 18 components and 78 parameters to permit evaluation of the environmental impact of large-scale water resource development projects. "Scores" are based on the magnitude and relative importance of specific impacts and "red flags" alert the user to major sources of concern. The proposed method was evaluated by the Corps along with seven others (Solomon, et al., 1977) and continues to have considerable promise for future evaluations.

In 1974, C. S. Holling published a paper through the International Institute for Applied System Analysis (Holling, 1974) which shows some parallels to the paper previously described (Dee, et al., 1973) and which has considerable

significance to the field. Holling describes the essential characteristics of an environmental simulation model and proposes steps to be employed by the decision maker and his staff in utilization of the model for policy analysis. He encourages computer use to handle the large amounts of data and the complex interrelationship of ecological systems; he further proposes a modified Delphic approach utilizing a multi-disciplinary but technically capable group to limit and identify significant policy actions. Finally, he illustrates application of the "plan" on a development project involving a large hydroelectric plant in James Bay Territory, Quebec, Canada, with Federal management specialists of Environment Canada.

A paper by Haber, Long and King (1975) attempts to apply many of Holling's ideas regarding complex ecological systems modeling to a U. S. Corps of Engineers project plan on the Upper Mississippi River. It is noteworthy because it is based on theories of ecological resiliency and because it attempts to translate some of Holling's proposals to a "nuts and bolts" project.

A study of the intricacies of systems analysis, not its application, was published by several authors, including one of Holling's earlier collaborators, in a paper by Rogers, Fiering and Harrington (1976). This paper "represents early efforts to define a single problem as the focus for a multi-faceted study of systems analysis applied to planning and design of water resource problems."

The papers described represent an attempt, to a greater or lesser degree, to perfect a method for quantification of environmental quality, particularly in regard to water quality. The description of the philosophy engendered by H. T. Odum in the paper following is far more comprehensive in its entirety. However, this paper attempts to deal with its general principles, application and use for analysis specifically as it applies to water resource problems.

ENERGETICS

DEFINITIONS

The term energetics has been used widely in biological circles since publication of an outstanding test by Lehninger (1965) which deals with transfers of biochemical energy in a physiological sense. The definition of energetics from Webster's American College Dictionary is: "Energetics is the science of the laws of energy." However, energetics as used to describe concepts elaborated by H. T. Odum in a number of publications (Odum, 1971; Odum, 1973; Odum, 1974; and Odum and Odum, 1976) involves application of a number of accepted scientific principles and cannot be so simply defined. In this paper, Odum's concepts will be referred to as energetics although he does not use that specific term in his publications.

The principle that unifies energetics is that energy is the source, and acts as the control on all aspects of human and natural existence. This principle is used by Odum in systems analysis by application of simple laws of energy use and dissipation to macroscopic systems of a perturbed and unperturbed nature. (A system is accepted here as anything that functions as a whole by the interaction of organized parts.) These laws, so often stated in elementary physics texts, are repeated and described here in a systems context:

(1) <u>Law of Conservation of Energy</u> - Energy is neither created nor destroyed. In macroscopic (complicated) systems analysis, this law demands a strict accounting of all energy inflow and outflow.

(2) <u>Law of Degradation of Energy</u> - In all processes, energy loses the ability to do useful work. Energy with the ability to do work is potential energy and is useful; energy that has done work may be degraded to a point where it is no longer useful. From this law comes the concept of <u>entropy</u>, which simply says that a system proceeds from order to disorder during energy degradation. It also says that energy undergoes change from a concentrated to a dispersed form; for example, use of concentrated fuel energy such as petroleum results in dispersal to motion and heat energy. The concept of entropy reflects on the quality of the energy and the important possibility of its continuing usefulness to humans in a more dispersed form.

(3) Systems Which Best Use Energy Survive - The principle of maximum power. That system survives which, in competition with other systems, uses energy most effectively by: (1) storage, (2) feedback to increase inflow, (3) recycling, (4) organizing controls for adaptation and stability, and (5) setting up exchanges with other systems to meet special needs.

Odum's energetics concept is built on the framework of these laws. Reference will be made to them in specific and generally in the discussion following.

COROLLARIES

In Odum's publications (principally Odum, 1971; and Odum and Odum, 1976), a number of ideas may immediately be deduced from these laws. These are stated here as corollaries not in a formal or mathematical sense, but as logical extensions. They are first presented as simple statements and then elaborated:

(1) Energy availability is a vital key to the development, growth and interactions of complex systems.

(2) Energy is transformed or degraded by use.

(3) To be used, energy must flow.

(4) Energy can be stored, in which case depreciation occurs.

(5) Energy can exert controls on the systems.

(6) Various forms of energy may interact.

(7) Energy is a form of currency.

These corollaries may be applied to a wide variety of systems and it is helpful to visualize one or more of the following for purposes of discussion: ecosystems, economic systems, geologic systems, meteorologic systems, political systems or systems of religion. An ecosystem is an apt example because it is simple (in comparison with, say, a human society), well understood, and may help explain more complicated system reactions due to its inherent temporal and spatial limits. In the following elaboration of corollaries, reaction in an aquatic, single-celled, photosynthesizing plant community is used as the dominant example.

Energy availability explains many changes and interactions occurring in a complex system. For example, in an aquatic ecosystem with no intersystem input, energy is obtained when light quanta (from sunlight) are absorbed by green plants; energy is then fixed by processes of photosynthesis. When energy from sunlight is readily available, growth of individual plants and the entire community occurs; when energy is less available but equals that necessary for sustenance (for respiration, transport and other metabolic processes), a steady state occurs in the system; where energy does not meet requirements for sustenance, the system must decline.

In the case of excess energy, the resultant growth of individuals facilitates reproduction and a continuing excess will cause the generation of more individuals. Should there be limits (e.g., nutrients, CO_2, space) on reproduction, storage of the fixed energy may occur through formation of fat, oil or starch globules in the individuals. This, in effect, gives the energy-rich community a competitive advantage over others with less energy by endowing it with vigor necessary to survive in case of catastrophe. Should the community, for some reason, be deprived of some part of its energy source, it can continue to thrive on stored energy; or, should its source be cut off completely, the stored energy permits it to encyst or form a protective layer or in some other way prepare itself for survival during the shortage. Storage of energy during periods of excess thus increases the options of the community and permits it to act flexibly during periods of change in energy availability. It is worth noting that when excess energy sources are in decline, and where the community does not have stored energy, the concept of conservation, of "doing more with less", is probably counter-productive since it reduces the ability to act flexibly and may only extend the life of the community for a short time. The possible impact of conservation in terms of its national meaning is discussed and illustrated below.

In some aquatic plant communities, excess energy is used to produce substances (exocrines) which either limit growth within that community or limit growth of possible competitors. This is an example of energy use to exert controls and effective energy use to reduce competition. It also illustrates that the higher the amount of energy freely available (meaning, in this case, sunlight), the less dependent that community is on external sources and the more competitive the position of the community in respect to others.

It should be clear that with the knowledge now avail-

able, the effect of increasing or decreasing the sunlight to a plant community is predictable within some limits. A great deal depends on the kinds (species) of organisms under consideration and the mechanisms of response available within each organism as part of its genetic heritage.

Energy availability has special meaning to the world at this time. Since the Arab oil embargo of 1974, global users of oil have discovered that supplies of easily convertible energy are both finite and unequally distributed. Developed nations with low sources of conventional energy and a high industrial output, such as Japan, the Netherlands and France, find themselves in desperate economic circumstances; developed nations with alternative energy sources such as coal and a similarly high industrial output, such as the U. S., Great Britain and Germany, have had to exploit these alternative fuels to retain their positions in the international economic market; undeveloped nations are finding more and more economic barriers to the orderly exploitation of their resources.

Use of alternative fuels by these countries is not an undesirable end from a nationalistic standpoint since it may promote economic independence. However, with sage pricing policies, as are presently employed by the OPEC (oil producing) countries, the costs of alternative fuels can be maintained at a slightly higher than economic level in countries without or with low supplies of oil. Thus, with coal for example at a slightly higher cost, the nation in question still cannot compete internationally, loses trade, loses its international position and to some extent lowers its social standing. Control over inexpensive energy sources and the availability of that energy clearly rewards the Arab nations with an inordinate degree of power in our present global system.

To complete this logic, where a nation accustomed to a high international standing and standard of living attempts to maintain these advantages by stringent conservation of its resources, it may reduce the national capability to develop, and cause it to lose its competitive edge in any case. This can occur through a number of routes: where artificial controls are placed on prices (of oil, for instance) through ceilings and taxes to reduce total consumption and thus imports, the incentive to explore for new domestic sources or to exploit marginal sources may be lost. In this way the flexibility of domestic supply is lost.

In a differing vein, a return to less environmentally favorable fuels, such as coal, involves certain unavoidable

environmental and economic costs. The environmental cost of dirty air is energetically calculable and of no small consequence both in terms of human health and in money expended to reduce its impact on buildings, automobiles, land, and water.

It would be wiser in a nation like the U. S. to use both domestic and foreign oil to develop the hardware for alternative, less exhaustible energy forms such as solar and geothermal sources. In the short run this may be expensive, but it corrects for our lack of foresight and just as in the phytoplankton above, places us in a flexible, competitive position as energy (oil) increases in price, or (to the same end) diminishes in supply.

<u>Energy is transformed or degraded by use</u>. Again, using an aquatic plant community as an example, the sunlight absorbed during photosynthesis is taken in as quanta and transformed to a basic sugar. The sugar becomes the energy source to the living cells and it may be changed through further processing to some form of energy for storage. The initial source was light quanta; the usable source becomes sugar, starch, fats or oils.

This transformation is complex and will not be elaborated here, but suffice it to say, at each transformation, energy is dissipated. Excitation of the light creates heat in the photosynthesizing cells and is given off; the cell itself metabolizes and gives off heat; transformation to the final source, sugar, produces oxygen which is given off into the surrounding media. Of the original input of light (an infinitesimal part of that actually available to the plant), only a very small part remains for utilization or storage. Degradation takes a serious toll.

It is important to observe that in the case of photosynthetic conversion of light to plant sugars, the quality of the energy is increased. That is, the caloric value of the sugar represents an accumulation of quanta; it is, in effect, concentrated light. Green plants cannot directly use sunlight as energy for a number of reasons: (1) because it is so dilute; (2) because light is not transportable; (3) because this energy cannot be used as a metabolic fuel by plants in their evolved form; and (4) because the quality, or caloric value, or sunlight is so low. Sunlight is low quality energy. Energies of differing quality differ in their ability to do useful work. As an aside, this is the reason that solar energy has not been readily "harnessed" for human use; enormous amounts must be collected to constiture an effective amount.

To go one further step with the aquatic plants, a simple and effective feedback mechanism operates during photosynthesis. The parts of the plant (chloroplasts, organelles) which carry out the conversion of light to sugar are metabolically subsidized by the light to permit them to increase the quality; some part of the light energy coming in is used by these plant parts to sustain their own existence, increase their number and for repair. This process is facilitative and can be perceived as a primitive but effective process to more effectively use the available energy.

To be used, energy must flow. Examples of the action implied by this corollary have been cited many times in the previous discussion, beginning with the flow of light quanta. Were the light kept from the aquatic plant system completely, the community would decline. Similarly, within the plant or plant colony, if the product of photosynthesis were not transferable inter- or intracellularly to perform metabolic work, the process would accomplish nothing. Use is dependent on flow and the transfer is a necessary function. When the entrance of light comprises the initial force, the subsequent concentration, use or storage is the result and the consequent degradation in caloric value completes the total process. The effectiveness with which initial capture is made, the amount of energy dissipated during conversion, storage, or by exerting control, and the biomass of organisms produced reflect upon the efficiency of that process. Basically, this means the ratio of input to output, including dissipation at all phases of the process, must be considered and calculated for the true efficiency. It is vital that these calculations be carried out completely to achieve real accounting and to understand the system under consideration. Clearly, the rate and the end point of the system may be measured by energy consumption, thus permitting predictions.

It is worth noting that in the real world of an aquatic plant community, the accounting is conducted with impassionate precision: the organism which is most efficient is the one which survives. An understanding of energy and energy flow of a given organism or group of competing organisms would do a great deal toward elucidating the processes of evolution.

The last point to be made regarding energy flow is that, although the energy initially entering the plant is concentrated or stored during photosynthesis, the ultimate use for normal plant metabolism results in dispersal. This occurs through heat losses, through losses of plant parts, through

plant products of various sorts and is culminated by death and subsequent breakdown of the cells to their chemical parts. In speaking of loss, it is only a loss to the individual or community; the energy remains within the system in some form.

Energy can be stored, in which case depreciation occurs. The depreciation of stored energy is a difficult one to illustrate using the aquatic plant community previously cited without an in-depth knowledge of plant physiology. It should be obvious that the production of some plant storage product is energy-costly; costs accrue by normal sustenance of the part involved in the conversion, by sustenance of the container (usually another living plant part), by transport of the storage product or raw material into the container, by transport out of the container, by conversion of the stored product to a usable form, by transport to the site of use, and by the ultimate use for whatever purpose. Degradation may occur in a passive sense through leakage of the storage product or actively through use of energy in the product to maintain it against a concentration gradient.

Energy can exert controls on the system. The ultimate control exerted by energy is primarily through its availability, but at numerous points in the life of an aquatic plant community, other controls are activated to prolong life or increase efficiency; some have already been mentioned. Within the plants, control of production and energy flow is exerted by such mechanisms as opening or closing plant pores to permit entrance of raw materials, by opening or closing of surfaces critical in collection of light, and by positioning of the plant to maximize collection. Other controls are exerted by the organism's size, by its solitary or colonial nature, by its ability to organize or develop division of labor within the cell and by the degree of enzyme catalysis (control of chemical rates by substances which are not themselves necessary to the process). As mentioned, certain plants are known (and many are suspected) of producing exocrines, or plant products, in very small amounts which can limit either the proliferation of their own kind, or of other species of organisms; thus, intra- or interspecies competition may be regulated.

Clearly, these controls are costly in terms of energy: specialized cells are maintained, extraneous products are dissipated, more heat is dissipated and efficiency is decreased. However, the ultimate effect is to increase the ability of the organism to effectively use the incoming energy and to reduce competition by less effective organisms.

Consider a free-floating plant; a highly adapted,

highly productive organism. To maximize energy collection, the plant floats near the surface; when the surface area becomes crowded, the penetration of light energy is decreased by the sheer number of plants, and the less adaptive plants below the surface suffer a decline. This in turn prevents limitations of growth which might occur through insufficient nutrients in the water column; an effective (and marvelous) control mechanism.

To add to this discussion on energy controls, it should be emphasized that the system of energy in use is determined by the kind of energy available. If sunlight were completely cut off from our aquatic plant community, organisms utilizing other sources would increase in number to predominate. It is a little hard to imagine loss of a source so basic and so the idea seems somewhat absurd, but in more complex communities (societies) the ability to switch energy sources may be necessary to survival. In water, a select group of bacteria survive through their ability to derive energy from iron and its oxides rather than from organic material, a perfect example of this adaptation.

As a final comment, where energy is added to an aquatic plant community from external sources, it may increase the effectiveness of the system. These external sources could consist of nutrients in the inflow from an adjacent lake, pond or stream, or from land run-off. However, depending upon the degree to which the energy is used, the organisms may become dependent upon these external sources to a point where they are no longer independent converters of basic sunlight. The effectiveness of the use of this secondary source may cause the organisms to become vulnerable to a point where survival is threatened, should the external source be reduced or removed.

Laboratory cultivation of living organisms is perhaps the most familiar example of energy subsidization in an ecological sense. In phytoplankton cultures for instance a number of environmental factors may be controlled which impinge on energy utilization, including: the availability of CO_2 and nutrients, temperature, and the periodicity, intensity, length of exposure and quality of light. These parameters are monitored and regulated to produce maximum numbers of organisms, usually of a single species, and provide completely artificial living conditions. Such conditions may produce lab-adapted organisms and through selection, strains of organisms with little capacity to exist in nature. Although examples of the return to a natural system and consequent survival of phytoplankton are unknown to this author, numerous examples of the return of animal species including

primates, wild cats and even fishes seem to bear out the notion that energy subsidization creates, along with a number of other factors, an inordinate dependency on the energy subsidy and decreased ability to survive. In cultivated or domesticated animals there are frequently behavioral modifications which add to the difficulty of assuming an harmonious position in a natural system.

Various forms of energy may interact. Once again, examples of this corollary have been cited previously, The secondary source in the paragraph above consisted of energy in the form of nutrients; in other words, organic or inorganic compounds available for plant use. In combination with the energy-fixing capacity of these photosynthesizing plants, this chemical energy can be readily assimilated. Within the cells, the process of metabolism implies the application of physiological energy to the chemistry of the cell, to promote transfer of nutrients, plant products, plant wastes, toxins, disease organisms, and gases essential to life; to produce products, wastes, toxins and gas products; to transport actively the same substances through membranes and against concentration gradients and so on. Another closely related example occurs due to basic physical law that says the speed or rate of a reaction or process is in some direct proportion to the heat applied to that process. It is simply a question of speeding up the molecular motion of the materials involved. So, the sunlight beaming down on the aquatic system is not only utilized by the plants through photosynthesis, its infrared component energizes and speeds up molecular motion in the surrounding media endowing it with heat, or increasing the temperature. When the heat of the media increases, it increases temperatures within the plant cells and the rates of the chemical process are increased. The primary energy source, sunlight, is used interactively with the chemical energy in the plants.

Energy is a form of currency. Energy has value; it is measured in calories or kilocalories which are, in turn, a measure of the ability of that particular energy unit to raise the temperature of one cubic centimeter of water one degree Celsius (C), from 15 to 16 C at one atmosphere of pressure. Energy is transferable; it may be transferred within an organism or from organism to organism in a variety of forms. Perhaps the easiest to consider is the case where one organism consumes another. The accumulated chemical energy of the prey is transferred to the consumer. Other transfers of a similar sort occur continually. It is an unfortunate truth that it is usual in calculations of energy input to output in agriculture, forestry and many other industries, to ignore, or at least take for granted, the value of natural forces, and natural energy flow. These inputs

do represent considerable value especially to industries directly dependent upon the conversion of light quanta to living material, but it is important to realize that natural forces have a significant role in most human industry and activity. A steel mill for instance use fossil fuel with a calculated value which represents concentrated light energy and other earth forces of eons ago. It also uses water from a nearby river for cooling, for steam, for process water and for disseminating wastes without calculating its value. Meteorological forces put the water at an elevation that causes it to have potential energy and this force causes it to flow and to pick up minerals from the substrate; biological systems utilize the minerals and modify nutrients from land contribution and have a direct impact on its purity or water quality. Both the amount of water and the purity dictate the extent and the uses to which the water may be put by the industry. Where purity is critical, in stream systems for example, the water quality as it comes from the river dictates the amount of money that must be expended to achieve the required level; the volume dictates to some extent the potential size of the industry. One may impute the value of water quality by the cost of clean-up as currently required by governmental regulation before returning the water to its course. When benefit/cost analysis is conducted economically or environmentally, it is essential to enter the enormous contribution of natural energy into the account.

Since humans think of currency as dollars or an appropriate surrogate, it seems important to note that energy can be given a dollar value. A glance at a home heating bill should be convincing evidence. In addition, in a society and world conditioned to the use of petroleum as the dominant energy source, as petroleum is perceived as decreasing in availability, the energy stored in that form must become more valuable. As currency, energy has currency.

Summary. The purpose of the preceding definitions of energetics is to provide a context in which to consider energy; the purpose of the discussion of the three laws is a reminder of the theoretical base upon which energy considerations are made. The corollaries were distilled from ideas in Odum's publications and are illustrated using an aquatic plant community because it seemed most easily understandable using a single, simple system. Despite the limitations of this single example, the corollaries translate the theoretical to the practical and make way for the next step, the application. It is worth emphasizing that Dr. Odum's contribution has not been the discovery of new laws of energy, but rather a simple translation of these fundamentals, and development of a method for application to questions of global importance.

ENERGETICS ANALYSIS

The method proposed by Dr. Odum for systems analyses of macroscopic systems through energetics consists of the following steps, first simply stated and, second, elaborated.

(1) Identify and describe all relevant components and processes of the system under consideration.

(2) Structure a diagram of those components indicating interactions where they occur.

(3) Program and run a computer simulation of energy input, component interaction, output, and energy losses for the system using such data as may be available for quantification.

(4) Structure a simulation model of the system.

IDENTIFY AND DESCRIBE RELEVANT SYSTEM COMPONENTS

As mentioned under "Definitions", a system is here used to refer to any whole that functions by the interaction of organized parts. Identification of, for example, components of an aquatic ecosystem would consist of listing the following:

(1) total solar energy reaching the system

- (a) direct (light quanta directly from the sun)
- (b) indirect ("skylight" light disseminated after the sun sets)
- (c) incidental (reflected, refracted or diffuse light)

(2) total energy impinging on the system (other than solar)

- (a) gravity
- (b) geological structure and formation
- (c) streams and exchange from other water bodies
- (d) land run-off (materials reaching the system via water)

(e) air loading (materials reaching the system via air)

(3) energy within the system but available only periodically

(a) bottom sediments

(b) materials bound in living materials and available seasonally

(4) total energy loss from the system

(a) system outflow

(b) harvest

(c) heat losses

(d) air emissions

(e) bound organics and inorganics entering the sediments

(5) primary producers--carbon-fixing organisms (autotrophs)

(6) primary, secondary, tertiary, etc., consumers--non-carbon-fixing organisms (heterotrophs)

Further breakdown of primary producers into fixed and floating plants, and consumers into benthic, pelagic and littoral organisms could be made, but are unnecessary complications to this example.

Other types of systems could have been as easily used as examples, for instance: the water system of a town; a primitive hunting society; a modern developing nation; a seaport or an agricultural project. In each, the principal energy sources, uses, interactions, and outputs are identified. Feedback, where some of the potential output is used to enhance, or to improve the quality of some stage of energy use, or any other interactions should be carefully considered. Energy losses to the system and energy subsidies are sometimes difficult to perceive, but their identification is especially critical toward achieving balance.

STRUCTURE A SYSTEMS DIAGRAM

Diagramming is commonplace to systems analysts; it per-

mits the viewer to put the components into place in respect to the other components. It is a visual reminder of the interactions between parts and prevents omission of significant parts. All components identified in Step 1 should be included.

Dr. Odum uses a series of symbols of his invention; these are contained in both major publications on the subject of energy (p. 38, Odum, 1971; p. 269-70, Odum and Odum, 1976). Use of these symbols is not mandatory, but standardization would be helpful. There are perhaps two consummate rules of use: (1) according to the first law of energy, input must balance output, and (2) money (=value in $) flows in an opposite direction to energy. The first rule is obvious. The second says that the value of energy in dollars is returned to the source; the user compensates for the energy from the sale of the resultant product.

PROGRAM AND RUN A COMPUTER SIMULATION OF THE SYSTEM

Relative energy values of the components of the system (from Steps 1 and 2) are programmed into a computer and the program is run to simulate various magnitudes of input, interaction and outflow, as well as operation with differing components in the system. As can be seen immediately, this provides the investigator with a complete range of predictive capabilities. One can show, for instance, what might happen to a producer community with an additional hour of sunlight each day, observe the competitive advantage of an organism with a higher turnover, predict the reaction of a community/system into which an additional competitor was introduced, or see the decrease in a population of aquatic plants where turbidity is increased due to the introduction of suspended solids. In a social system one might show the amount of compensation required to maintain an energy source, the implicit value of the use, the worth of the user and perhaps some idea of the economic or social value of that consumer to the entire system or universe. In addition, simulation stimulates the imagination of the investigator, demands precision, opens new questions and can be a powerful force toward obtaining more accurate, more reliable systems data. Simulation permits the investigator to reexamine his thinking and the relevance of his assumptions about the real world.

Odum makes a strong case (pp. 255-67, Odum, 1971) for analog computation in energy circuits; the analog circuit imitates the energy network (from Step 2), for each energy pathway there is a wire and for each system component, an electrical component to simulate its reaction. It is hard-

ware substituting for a real world system. This electrical system functions in proportion to the flows and provides rates of reaction without special devices, the introduction of constraints or other calculations, where linearity is expected. For example, a curve of population growth and decline can be reproduced using the appropriate forces and pathways.

In digital computation, a set of precise instructions is entered into the computer to simulate a precise set of conditions; from this, an answer is generated, entered into the machine, and may be printed. The next set of conditions entered into the machine through a loop combines with answers from the previous question, and a new answer is entered and may be printed. Digital computation can also reproduce a curve of population growth and decline, but within the machine it would actually be a series of points with heights approximating the curve. With this perhaps simplistic explanation the advantages of analog computation can readily be seen. However, the most telling argument for use of digital computers is their availability via the nearest telephone and, contrarily, the lack of analog capability in most computer facilities.

STRUCTURE A MODEL OF THE SYSTEM

Mathematical modeling is the current fashion in many technical fields; modeling in this sense is an attempt to represent a system using mathematical functions in such a way that the functions vary as they would in the real world. Models serve a number of useful purposes; they: force thorough thinking, force recognition of system components, aid in making assumptions, and can be used for prediction of changes through time or other variables. Models provide accurate answers in direct proportion to the accuracy of the input and have supplied the impetus for many kinds of data collection and verification. Too frequently models are considered an answer; without verification, models result only in questions.

Structure of a model from the simulation (of Step 3) helps the investigator recognize similarities in the interactions within an energy system. By mathematical calculations, the approximation of a system to steady state, various rates of growth, accelerated growth can be compared with other systems and the predictive capabilities of the model can be exercised.

APPLICATION

To understand and apply this method of energetics analysis to macroscopic systems, the investigator must:

(1) Have a grasp of the basic laws of energy;

(2) Accept the reality of energy as the controlling factor in all complex systems;

(3) Accept a systems view and understand the language of systems diagrams;

(4) Be prepared to reconsider preconceived notions of trends and values in complex systems.

BASIC UNDERLYING CONCEPTS

One of the more difficult aspects of evaluation of environmental quality or change in environmental quality is development of realistic values for the benefits and costs. The economic costs, due to a decrease in shipping caused by an undredged channel, flood-loss of life and property due to an unconstructed dam or diversion, or the inconvenience to a community with a poor water supply, can and are easily calculated; however, the costs for maintaining, or of returning an area to a specific state of environmental quality are extremely elusive. One of the major advantages of accounting by energetics is its capacity to supply values for a complete system, and for such change as may be contemplated or anticipated in its condition. These values are not developed by census of esthetic appeal, but represent the contributory value of the energy in that system to a society in a local, national and global sense. Concepts which would facilitate evaluation of this sort are discussed in the section following.

ENERGY UNITS

All forms of energy can be converted completely to heat; therefore, the energy unit for measurement of quantity is the calorie. Since energy diagrams frequently involve enormous amount of heat, the kilocalorie (=1,000 calories) denoted by K/Cal (with a capital C) is suggested.

Approximate equivalent values for conversion of other common energy units follow from Odum and Odum (1976):

1 K/Calorie	=	4 BTU (British Thermal Units) 3,000 foot-pounds 4,000 joules 1 watt-hour
1 K/Calorie/day	=	5.61 hp (horsepower) 4.186 kw (kilowatts)
1 K/Calorie of electric energy	=	4 Calories of coal in a stream electric generating plant, or 0.25 Calories, FFE (fossil fuel equivalents)

NOTE: Production of 1 Calorie of electricity requires burning 4 Calories of coal due to heat loss, frictional losses, process inefficiencies, etc., in

the plant. Since energy from fossil fuel is widely used and is the subject of great present-day concern, FFE, or fossil fuel equivalent is a unit found in many energetics calculations.

ENERGY QUALITY

This term is used in energetics to mean the concentration of energy, and its consequent level of usefulness for human purposes.

Although all energy can be measured in units (see preceding section), there are various thresholds, depending on energy type, which limit its usefulness to humans. For example, it has been suggested that waste heat produced by electric power plants be employed for some beneficial human use, rather than be dissipated to the atmosphere via water. Although turbine temperatures may reach 537 degrees C in a fossil-fueled steam electric plant, output temperatures dissipated via the cooling water are frequently of the order of 32 degrees C.[1] This is low energy heat degraded in quality. It may be useful for heating homes, greenhouses or culture ponds where large quantities are available and distances between sources and uses are small; it is not useful for purposes requiring a concentrated heat source.

Within the plant, and before it is degraded to lower temperatures, heat generated by the fuel is used many times: first, to heat the boiler, then to heat the fuel, to pre-heat the boiler, and to pre-heat steam. This raises the quality (i.e., concentrates heat) in "new" fuel or "new" boiler water to bring it to useful temperatures. The degradation that takes place at each step satisfies the second law and waste heat is vented.

Clearly raising the quality of energy costs energy. The gradation of quality proceeds from a low of sunlight, to wood, to fossil fuels, to electicity, and reaches an energy/quality height at computer capability and the ability of humans to assimilate and process information. Information then is at the zenith of the scale of energy quality. The following

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[1] Steam electric plants are purposely designed with temperature differences of this magnitude because energy is costly, and efficient use means wringing out the ultimate vestige of usable heat. Even so the modern steam electric plant has an efficiency of only (about) 45 percent due to limitations in the Carnot cycle, frictional and heat losses, etc.

formulation of energy quality appears in Bayley, *et al.*, 1976a:

$$\text{Energy Quality Factor} = \frac{\text{Input and Feedback Energy}}{\text{Output of Original Quality}}$$

QUANTIFICATION OF NATURAL VALUES

The crux of the problem of measuring environmental quality is obtaining data accurately reflecting values of a natural system and its components to man. In energetics, this means accumulation of data on the contribution or use of energy by each system component. This might be accomplished by:

(1) use of existing data sources (there is a data-rich literature available; see Odum, 1971; Odum and Odum, 1976; Bayley, *et al.*, 1976a; and Bayley, *et al.*, 1976b).

(2) development of new data (expensive, time-consuming).

(3) approximations tested through an energetics simulation and augmented where necessary.[1]

To illustrate (1) above, see the following tables and figure in Odum, 1971: p. 47, Table 2-1; p. 50, Table 2-2; p. 83, Table 3-3; p. 104, Figure 4-1; p. 136, Table 4-2. See also Table 6-1 (p. 79) in Odum and Odum, 1976, and numerous figures and chapter bibliographies in both publications.

Illustration of point (2) above is not possible but suffice it to say that development of new data cannot be undertaken without a thorough knowledge of the published literature. This alternative is viable only after alternative (1) has been found insufficient. In Bayley, *et al.* (1976b) insufficient data on the environmental costs of several aspects of transportation of commodities seriously impeded the study.

This is similarly true for alternative (3), value approximation. In addition, alternative (3) requires following the steps enumerated under "Energy Analysis" (p. 24): iden-

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[1] Walker, R. and S. Bayley. 1977. Quantitative assessment values in benefit-cost analysis. (Mimeo) Dept. of Environmental Engineering Science, U. of Florida, Gainesville, Florida. 23 p.

tify components, diagram and quantify components and component systems as far as possible, run a computer simulation, and structure a model. The predictable outcome of this exercise will be:

(1) an output in terms of energy,

(2) evidence of the completeness with which the system has been constructed,

(3) a measure of the relative significance of subsystems and components,

(4) a demonstration of the capacity of the system and its parts to absorb change, and

(5) evidence of weaknesses or absence of critical data and information.

This should provide insights permitting the investigator to continue to use or to modify the approximations. In a sense, this method consists of working backward from the "answer" to the correct or accurate data.

It is important to recognize that data are available in many forms and may be convertible to the desired values for formulation. Some of those are: incoming energy, primary productivity (energy-fixing), primary consumption, efficiency (of energy conversion), power requirements and fuel value. It is also possible to measure value or to quantify through calculation of replacement energy (see p. 155, Odum, 1971) or by optimization techniques (see p. 178, Odum, 1971).

In addition to an energy evaluation of systems such as rain forests, prairies, warm springs and marine ecosystems, energy absorbed and fixed by terrestrial and aquatic organisms and consumed at various levels, Odum mentions the importance of evaluating the impact of chemicals introduced into the water (p. 45, Odum, 1971). Value of the resource as a solvent, reactant and biological moderator of chemical pollutants is compared to its value for hydroelectric energy. Data on national energy expenditures for pollutant absorption are available through the Environmental Protection Agency's Effluent Limitations Program, the National Commission on Water Quality reports (NCWQ, 1976), environmental quality reports from the President's Council on Environmental Quality (CEQ, 1977) and the National Residuals Discharge Inventory (Luken, et al., 1976; Luken and Pechan, 1977).

MONEY/ENERGY CONVERSION

The relationship of money to energy is one of the more complex issues addressed in this paper. Energy flows inexorably through numerous complex systems in this biosphere, unaffected by human influence. The sun's energy falls onto the green surfaces of photosynthesizing plants, and flowers grow and forests sprout; these plants die and nutrients and biomass go into the soil making way for new plants. The sun's energy falls onto the land surfaces causing the air above to generate convectional currents, the generation of high and low pressure areas, and venting enormous power through winds. Warm, moist air is carried up over mountains and hills by these convectional currents, and the water precipitates, falling to the land; the water runs down the land in rivulets to the streams,then the rivers and is carried by gravity to sea level, throughout its courses releasing tremendous quantities of potential energy. But when these or any other forms of energy are harnessed by a complex society for human purpose, to do work, money is exchanged. Money is exchanged for the fossil fuel for a power plant, for construction of the plant, for transmission lines, for the workers who operate the plant and repair the transmission lines, and for the electricity that runs a factory or lights a home.

In essence then, it can be said that money is exchanged for, or represents, energy; it is not energy itself. In order to emphasize this interrelationship, a number of ideas which illustrate it are discussed below.

Money represents energy. In natural systems, energy (originating from the sun) flows without cost; there is only a cost when that energy is not effectively used. In managed systems, there is either an exchange of money (e.g., for coal, oil, gas) or an indirect cost for harnessing the energy (e.g., building an hydroelectric plant, planting a monocultural crop). In natural systems, effective use of energy may depend on feedback, an energy expenditure within the system to enhance use. In managed systems, feedback is supplied by improving turbine design, recycling heat or increased investment in plants; money becomes the feedback. Clearly, this is oversimplification; money is exchanged to pay the draftsmen to design the new turbine, to prepare the metal, to replace the old turbine, to test and repair the new one, to operate it on-line and to dispose of the obsolete part. In addition, money is exchanged to borrow the money to pay for the improvement, for calculating the cost, for printing the bills, for signing the checks, for the telephone to begin negotiations with the bank for the improve-

ment, and for the administration building in which the decision was made to undertake the improvement. Money is also exchanged by the energy that goes into the education of each of the people involved, with the people having the greatest accumulation of knowledge or training receiving the greater proportion of remuneration. All this for the ultimate purpose of increasing the efficiency of energy use, forced by the exchange of money.

In a complex network of energy supply and demand where output is dependent on supply at several stages, energy feedback may act to augment supply when it becomes short; when the supply is excessive, either the self-regulation of feedback will be withdrawn, or some of the output will go into storage, or to improve the system. This is analogous to what is known as an IO-model (input-output) of production industries dependent at various stages on the output from other industries. In a model where the final output is farm machinery, when the supply of steel is short, steel prices go up; money supplies the feedback to stroke the supply. When steel is abundant, either the price falls, the steel manufacturer puts some of his product into storage, he develops new markets at a more favorable price, or the steel is used to improve the output of his plant. In either case, energy and the work it can accomplish is compensated by an exchange of money.

In these examples, it is easy to understand why the connection of money as a causative force in the flow of energy is so often forgotten.

Money costs energy. Although this point was touched upon in the previous illustration, it is reiterated for emphasis here.

All transactions involving money require work or expenditure of energy. Although actual heat losses are small, as the exchange or storage of money becomes more complex and more highly regulated, the costs increase.

This is not a difficult concept to visualize. When a farmer produced more than he could use, he traded the excess for something he wanted or needed at the local country store. The exchange was between two people, did not even require currency and was payment for work. Today a similar payment for work involves several large institutions, both federal and state governments, printing and recording of checks, printing currency, two dozen people and plush lobbies in the bank in which the excess is deposited. And the costs increase.

Money may be circulated. The flow of energy makes possible the circulation of money; manipulations of money may control energy flow; but money flow is opposite to energy flow. Money is used to pay for work done and work is done through the expenditure of energy.

Money may be stored. Storage of money may be accomplished in a number of ways: by simply storing currency (coffee cans seem preferable), by loaning it to a financial institution at interest, or by investing in a product, company or institution in hopes that that investment will increase in value. In any case, whether the money was directly earned or inherited, it represents the expenditure of energy and it is stored against the day that the investor decides he no longer wishes to work, his work becomes intrinsically less valuable, or he wishes to purchase some product with a value in excess of his current income. The analog in energy storage is immediately evident.

Conversion of energy value to money value facilitates comparisons. Placing a dollar value on energy permits comparison of economies in different societies, regions and nations, and through time. In this way, the relative value of a society, in terms of energy, may be determined. A primitive society relying primarily on sunlight as an energy source would be lowest on the developmental scale; sunlight is a diffuse form of energy. An advanced society which subsidizes development by use of fossil or nuclear fuels would be higher on the scale; fossil and nuclear fuels are concentrated forms of energy and increase individual ability to do useful work. The energy required to do useful work does not change, but the money exchanged for that work may change depending on supply and the value of the ultimate product. The current average exchange rate for work done is approximately 25,000 K/Calories per dollar in the U.S. (Odum and Odum, 1976). This means that a total of 25,000 K/Calories of energy is invested for each dollar of product.

Money exchanged for energy also permits evaluation of individual contribution. If the individual has a great accumulation of knowledge or experience (gained by the expenditure of energy), the value of his work increases. If the money exchanged for the individual's useful work exceeds that required for maintenance, it may be stored or saved for future needs.

Evaluation of money exchanged for useful work permits comparison of political or politico-economic systems. Capitalism seems to best approximate natural energy systems in its reward to successful units. In effect, this is feedback facilitating effective energy use; it is a self-

designing, self-regulating network. The lack of reward to the individual under other systems is not reinforcing and is unlikely to develop pathways of maximum productivity.

The principal goal in this section has been to establish the link between money and energy in a conceptual sense. The goal of either currency is systems management and in a complex society, money lubricates energy flow. Energy flow is an unchanging measure of accomplishment, of work done, and money may be a false reflection of this accomplishment to be used with caution.

INVESTMENT RATIO

An investment in economic terms is the expenditure of money for something offering a profit; an investment in energetics terms is an energy expenditure into the energy flow which offers to increase the structure and order of the system. An investment ratio (IR) is the relationship between purchased energy for feedback, to energy naturally available, expressed in fossil-fuel equivalents (FFE) (Odum and Odum, 1976).

When the rise of industrialized nations is reviewed, it is clear that they all began in an economy dependent on natural energy sources. These nations grew in industrial capacity as they augmented natural energy with high-quality, concentrated energy such as coal, oil, gas and, more recently, nuclear energy. It seems clear that efficient use consists of taking advantage of natural "free" energy wherever possible, along with the purchased fuels. Natural "free" energy not only means sunlight (hardly applicable to a typical industrial complex) and hydro-power, but the energy available in clean water and clean air as mediators of environmental effluents and emissions.

In the U.S., this ratio of use is about 1 unit of renewable energy to 2.5 units of purchased energy; the world ratio is 1 unit of renewable energy to 0.3 purchased. In a publication dealing with the difficulties of assigning dollar values to essentially free services, Kylstra (1974) reports 18,700 Calories (coal equivalent) per dollar.

Problems arise when industrial density increases, particularly in urban areas, to the point where natural energy in the form of clean water, clean air and unobstructed sunlight is no longer available, or is not cost-free. Thus, highly developed urban areas may have problems competing with less developed areas where these amenities are less costly. As national pressures to clean up the environ-

ment mount, this disparity is likely to get even greater.

An example of the usefulness of calculating an investment ratio can be found in the South Florida Study (Browder, Littlejohn and Young, [no date]), a document for planning the economics of land, water and energy use in South Florida. This report systematically overviews the region's natural and economic resources, accepts nature as a partner in resource management and questions preconceived ideas about growth trends, underlying causes and the desirability of growth. During the study, energy was found central to the carrying capacity of South Florida and it was suggested that a stable economy might be maintained by taking advantage of natural ecosystems fueled by solar energy and reducing reliance on fossil/purchased fuels. It was found important to re-examine land and water management practices to this end. Preliminary estimates of carrying capacity indicated the area is at or near its long-term growth potential.

In the area of water resources, reliance on fuel-based management caused the investment of almost 20 trillion Calories of energy in drainage and water control. This disrupted natural cycles, diminished potential natural contributions to the region and contributed to an investment ratio of 1 Calorie of renewable energy to 2.9 Calories of fossil fuel energy. This is high compared to the national average of 2.5

Based on the findings, it was recommended that South Florida allow its wetlands and waters to return to a more natural state, to deemphasize water control and obstruction, to encourage recharge and water storage, to protect the productivity of the coastal zone and, in general, to curb the investment of fossil fuel energy where natural energy cycles can take its place.

In another study in Florida by Bayley, et al. (1976a), three proposed water resources alternatives in the Upper St. Johns River Basin are evaluated using Corps of Engineers benefit/cost analysis and energetics analysis. Two of the plans basically recommend increased investment in the basin for flood control, water detention and irrigation; the third recommends no further action in these areas. Of these three plans, the Corps of Engineers recommended plan alone results in a favorable benefit/cost (BCR) ratio (1.21) with the benefits mainly in a reduction of inundation of agricultural land and increased irrigation water supply; a plan by the Florida Game and Fish Commission does not result in a favorable (BCR) because these same benefits would not be achieved; and a No Further Action Plan has essentially the same result. Analysis of the three plans using energetics

models indicated a fourfold reduction, or essentially, elimination of natural terrestrial contributions to the energy system of the Basin. Results of the analysis using investment ratio indicated an increase from 2.25 (compared to the national figure of 2.5) to about 6 using all three of the alternative plans.

Despite limitations in the capability of energetics analysis to deal with the large (147 percent) population increases projected, and the large averages involved, it was concluded that the alternative plans would replace contributions of the natural ecosystem with agricultural contributions and that this factor would intensify the dependence of the region on purchased energy.

From these two studies it can generally be concluded that investment ratio is a useful technique for analysis. If it is accepted that dependence on purchased fuel, with some attendant uncertainties in cost and availability, is desirable, IR will provide essential information not normally considered through conventional benefit/cost analysis.

NET ENERGY AND ENERGY YIELD RATIO

Net energy is that energy remaining after subtracting the costs of obtaining and concentrating it to a usable form (Odum, 1975); or the energy yield in excess of the cost of feedback (Odum, 1976). Calculation requires conversion of various energy forms to fossil-fuel equivalents.

In some cases, sources yielding no net energy of their own can be subsidized to provide a net yield. Current effort to capture solar energy requires enormous quantities of hardware to attain net energy. A decision must be made regarding sources which will yield sufficient energy to justify the investment. This can be determined by calculating the energy yield ratio (EYR), defined as: the ratio of yield to investment (in FEEs). In effect this is an index of the energy efficiency of a system and should be coming into wide use in energy development in the U.S. to make decisions regarding the best investment among the many alternative energy sources now under consideration.

A relatively sophisticated version of the uses of calculations of net energy and energy yield ratios may be found in Bayley, et al. (1976b): a framework study comparing energetics and economic evaluations of alternative shipment of commodities. Consideration of net energy is related to Lotka's maximum energy principle since minimizing energy invested in transportation maximizes net energy. Transporta-

tation modes considered were: barge, rail, coal slurry pipelines and transmission lines; these modes were generalized and were not compared for a specific project.

The results of this study were to indicate methods of analysis, and although an enormous quantity of data and calculations are presented, results in the form of completed, comparable energy yield ratios do not appear. This was largely due to a lack of detailed data on aspects of the impact of these respective modes and the costs involved. A great deal of reliance was placed on the economics, and energy conversions were made from expenditures to approximate energy flows.

In spite of the limitations on the results of this study, the pathways for comparison of alternatives for a specific project dealing in commodity shipment are well illustrated. In addition, data and information needs are carefully and comprehensively assessed.

ENERGY BENEFIT/COST ANALYSIS

The basic principle of benefit/cost analysis is the assignment of numerical values to benefits and costs, and arriving at decisions of social welfare by adding them up and accepting those projects whose benefits exceed their costs (Layard, 1972). Similar calculations are made for energy, but instead of an evaluation involving dollars, units of energy, preferably FFEs, are computed. According to Bayley, et al. (1976a), although energetics analysis is new and has not been extensively tested, it benefits from and can include economic analysis. This report on the Upper St. Johns River Basin observes that application of traditional BCR analysis is not considerate of societal costs, is sensitive to changes in discount rate (the value of a dollar today, compared to the value of a dollar in, say, ten years), and relies heavily on an extrapolation of trends. Energetics BCR analysis is characterized as considering societal costs, selecting future alternatives, and generating energy constraints. Table 3 in Bayley, et al. (1976a) compares the assumptions of general analyses.

Calculations of energy BCR (Table 17, Bayley, et al., 1976a) indicate that there is relatively little difference between the energetics of the three proposed plans for the St. Johns Basin; all increase the total energy of the region by a factor of 1.6. However, energy BCR shows quantitative changes from natural to agricultural photosynthetic contributions. There was an annual loss of natural energy worth 270 million dollars using the Recommended

(Corps of Engineers) Plan, and a 217 million dollar gain in agricultural energy using the Recommended Plan.

According to a paper by Walker and Bayley,[1] economic BCR does not include the value of natural systems and is restricted to pricings emerging from market interactions. Two methods are described which incorporate environmental degradation into the calculations of BCR to permit consideration of previously neglected costs. The methods are said to be equally applicable to increased natural benefits. To accomplish this, opportunity costs of lost natural values are discussed and a method for integrating them into net benefits is shown, and a means is described for using discount rate to account for the decreasing supply and increasing demand for natural areas.

Using an economic method of BCR, a comparison is made of the values of unaffected and project-affected natural areas for recreation, education, water storage capacity and water quality; the discount rate is weighted to give natural areas a higher value than in traditional methods. The energetics method computes the quantity of energy produced by natural areas and translates ecological impact into dollars by use of energy quality factors and the national investment ratio. This methodology indicates that it is possible to integrate national system values into a BCR framework. Although there is a wide discrepancy between the total environmental costs of the two methods ($11,196,150 versus $4,954,549), this is attributed to use of an hypothetical example and the lack of calculated values for the ecosystems in use of conventional benefit cost analysis.

LOTKA'S LAW AND MAXIMIZATION OF ENERGY FLOWS

Lotka's Law is better stated as a principle and was referred to earlier as the principle of maximum power: systems which best use energy survive. The original thinking comes from an old paper by Lotka (1922) in which he observes that "the advantage must go to those organisms whose energy-capturing devices are most efficient in directing available energy into channels favorable to the preservation of the species." This principle is extended to other complex

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[1] Walker, R. and S. Bayley. 1977. Quantitative assessment of natural values in benefit-cost analysis. (Mimeo) Dept. of Environmental Engineering Sciences, U. of Florida, Gainesville, Florida. 23 p.

systems, such as forests, seas, cities and countries by Odum (1973) who states the first requirement as maximizing opportunities to gain inflowing power, and second, as that utilization more effective and less wasteful than those of competing systems. In Bayley, et al. (1976b), it is stated: "Systems that can capture more energy can do more to predominate, meet contingencies, survive stress, and build structure for the long and short run." This principle has been described and elaborated previously in this paper (see pp. 12, 13, 19-22).

ENERGETICS APPLICATION TO WATER RESOURCE PLANNING AND DECISION MAKING

As has been amply demonstrated in previous sections, analysis by energetics does have application to water resource problems. The trap to be avoided is one of over-enthusiastically embracing a system without a cold hard look at the real potential and real limitations.

POTENTIAL

1. Permits an assessment of total environmental quality. When a change is contemplated or anticipated in water resources, an enormous number of factors must be considered as a basis for action. Physical, chemical, biological, economic and socially related data are collected and must be reduced to comprehensible proportions. Analysis by energetics summarizes impact by relating these factors to the energy of the system; it is the ultimate interdisciplinary approach.

2. Results in quantification of values for natural systems. In economic terms, energetics expresses a value for a non-marketable entity; developing this value has been a goal of economists and environmentalists alike. Its derivation by an ecologist with a thorough understanding of the biosphere is fitting, since, from a human viewpoint, the ultimate judgment of the health of a living system is biological.

3. Assumes a systems view. A water resource is a complex system; it is appropriate to take an approach which deals in a multitude of factors, which implies data reduction and manipulation by computer, and which permits review of a nearly infinite range of options.

4. Expresses a different view of water resources. The problem of assessing environmental quality has traditionally resulted in an economic approach. It has been, with some exceptions, a myopic view that assumes an accounting based on a dollar value. Given a proper hearing, analysis by energetics is likely to threaten tradition and to arouse both thought and action toward evolving other reliable methods of accounting.

LIMITATIONS

1. Is a relatively new, relatively untested method of analysis. The difficulty here is that the results cannot be

used in a comparative sense; newness itself although not seeming a liability results in uncertainly, suspicion, complaisance and lack of data.

2. Is complex. The obvious reply to this limitation is that the problems themselves are complex. The real barrier to launching a widespread assault on all water resource problems using this method is: (a) too few people have the background and training to deal with energy in such depth, and (b) the method requires an highly creative approach to problem solving.

3. The decision maker is forced to view a natural system as superior to one technologically augmented or achieved in total. This is perhaps the most serious limitation in that it may occlude further judgment. Energetics assumes that the best interests of humans in goals of social welfare will be served in a natural milieu. This must be demonstrated, not assumed.

CRITERIA OF APPLICABILITY

There are a number of criteria which might be considered useful in judging the appropriateness of a proposal for analysis; the following were taken from an article by Otto (1975) on the subject of energetics.

1. Simplicity. Is this evaluation methodology simple enough for routine work? As suggested in the section on limitations, energetics is complex, requires a comprehensive understanding of environmental systems and involves imaginative and creative thinking. It is hard to conceive of this as suitable for routine application at this stage.

2. Adaptability. Are the parameter and weighting factors employed by this methodology sufficiently adaptable to the kinds of local conditions typically encountered in projects? The variations that may be built into an energetics system approach are limited only by the creativeness of the decision makers and their ability to develop data.

3. Freedom from bias. Is the control or influence factor resulting from internal subjective inputs to the evaluation at a minimum? Bias in energetics is believed to be minimal; however, the literature developed so far seems to echo the ecological viewpoint that "natural is good." Although this may be true, it must be questioned at every stage of evaluation.

4. Responsiveness. Is the projection of public and community policies and preferences by this methodology at a maximum? The viewpoint of natural systems does seem to be an accurate representation of current public perception of environment.

5. Scope. How useful is the methodology for decision-making throughout the various stages of the planning process? One of the virtues of energetics analysis is its comprehensiveness, but conducting the analysis requires complete data and some serious commitment to a project. It is, therefore, probably most useful at some secondary stage of development, subsequent to some initial consideration of project feasibility, but prior to detailed planning.

CONCLUSIONS

1. Energetics analysis has the potential for use in assessing environmental quality in general, and water resources in specific.

2. Since energy inflow, interaction and outflow of water resource projects are extremely complex, so are their analyses.

3. Use of energetics as a management tool requires personnel with broad knowledge of the factors involved and a creative systems approach.

4. Energetics as a tool is data-limited; energetics has the capacity of application to an extremely broad range of projects, and lack of definitive data on specific impacts is the primary limitation.

5. So far, no other proposed analytic technique has the promise energetics has for total environmental assessment which includes quantification of values of natural systems.

6. Analysis of energetics is still in a developmental stage and is likely to gain in sophistication with each attempt at application to contemporary problems.

RECOMMENDATIONS

1. A small group of scientists should be appointed from within the Corps who have a demonstrated capability and interest in environmental assessment to:

   a. review current Corps projects and select at least three projects with a range of complexity appropriate for energetics analysis;

   b. seek to fund these projects for energetics analysis by a group, possibly academics, with a working knowledge of the techniques of energetics;

   c. review the results of these studies;

   d. deliver a judgment of these study results regarding their appropriateness to the Corps' mission.

2. If the results of this examination are negative, decline further investigation.

3. If the results are positive, engage a group to prepare, or to supervise preparation of a course of training in energetics analysis for working level planners and environmental scientists.

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